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Resonance effects of the electron distribution function formation in spatially periodic fields

Yu.B. Golubovskii†, R.V. Kozakov‡, C. Wilke‡, J. Behnke‡ and V. Nekutchaev§
† Saint-Petersburg State University, ul. Uljanovskaja, 1, 198504, Russian Federation
‡ Insitute of Physics, University Greifswald, Domstr., 10a, 17489, Germany
§ Ukhta Industrial State University, ul. Senjukova 13, Ukhta, 167300, Russian Federation

Calculations of the election energy distribution function (EEDF) in the striation-like sine modulated electric field are performed. Dependence on a spatial period length was investigated. Calculations were made for discharge conditions pR=2 Torr cm and i/R= 5 mA/cm and electric field E/p= 1.9 V/cmTorr. The presence of the resonances on the EEDF and macroscopic parameters are demonstrated. These resonances correspond to S- and P-striations that could be observed in experiments. The interpretation of the results, based on the analytical approximation of the numerical solution is proposed.

1. Introduction

Resonant EEDF formation in the spatially periodic electric fields occurs in the case when electron energy balance is governed by inelastic processes and the energy losses in elastic collisions over the period length are negligible. This kind of energy balance occurs in gas discharges at small currents and low pressures in inert gases.

Resonant EEDF formation was investigated in several papers. Analytical solution of the Boltzman equation was obtained in paper [1]. It was shown that the relaxation process of an arbitrary initial EEDF in the homogeneous electric field has a form of damped oscillations with energy period $U_{res} = U_{ex} + \Delta U$ and spatial period $L_{res} = U_{res}/E_0$, where U_{ex} is the excitation energy, ΔU is the small energy losses in elastic collisions and E_0 is the period-averaged electric field.

In spatially periodic electric field the EEDF is formed which depends resonantly on the value of spatial period [2]. EEDF has a specific maximum whose formation was explained as bunching effect due to the small energy losses in elastic collisions [1] and due to the presence of several excited states [3].

Present work is devoted to the analysis of the EEDF formation in the spatially periodic electric fields, study of the resonance behaviour of the EEDF and their interpretation.

2. EEDF in the spatially periodic electric fields

2.1 Kinetic equation

Boltzman equation for the isotropic part of the distribution function f_0 in variables of total energy $\varepsilon = U + e\varphi(x)$ and space coordinate x, where U is the kinetic energy and $e\varphi(x)$ is the potential energy of the electron, can be written as

$$\frac{\partial}{\partial x}D_\varepsilon(v)\frac{\partial f_0(\varepsilon,x)}{\partial x} + \frac{\partial}{\partial \varepsilon}V_\varepsilon(v)f_0(\varepsilon,x) = v\nu^*(v)f_0(\varepsilon,x) - v'\nu^*(v')f_0(\varepsilon+U_{ex},x) \quad (1)$$

where $D_\varepsilon = v^3/3\nu(v)$, $V_\varepsilon = 2m^2\nu(v)v^3/M$, $\nu^*(v)$ is the total frequency of inelastic processes and $\nu(v)$ is the frequency of elastic collisions. Velocities v and v' are related by the energy conservation law $mv'^2/2 = mv^2/2 + U_{ex}$. For numerical analysis of the equation (1) it has to be completed by the appropriate boundary conditions

$$f_0(\varepsilon,x)|_{U\to\infty} = 0 \qquad \left.\frac{\partial f_0(\varepsilon,x)}{\partial x}\right|_{U=0} = 0 \quad (2)$$

2.2 Calculation procedure

Equation (1) with the boundary conditions (2) was solved numerically by Cranc-Nicolson algorithm [4]. Calculations were performed for the electric fields with modulation degree $\alpha = 0.9$ and value of mean electric field $E_0 = 1.9\,V/cm$ which corresponds to the discharge conditions under the pressure $p = 2.0\,Torr$ and current $I = 10\,mA$. First it was solved for the case of the homogeneous electric field E_0 in order to obtain the value of the resonance spatial period L_{res} which was found to be equal $9.8\,cm$. Then equation (1) was solved for the different values of the spatial period L in the range $4 - 12\,cm$ which includes values of the first $L = L_{res}$ and second $L = L_{res}/2$ resonances. The values of the frequencies of the inelastic processes were increased by two orders of magnitude in order to obtain sharper resonance behaviour of the EEDF.

2.3 Results of the calculations

As the numerical analysis was performed for the increased values of the inelastic frequencies, the solution strives to that in the "black wall" approximation with the zero boundary condition at the excitation threshold $f_0(\varepsilon,x)|_{U=U_{ex}} = 0$. Results of the calculations near the first resonance are shown in figure 1. It is seen that at $L = L_{res}$ the EEDF has a strong modulation which decreases at other values of L.

Analytical solution of (1) under "black wall" approximation could be obtained [1] in the form of series expansion relative to the small parameter

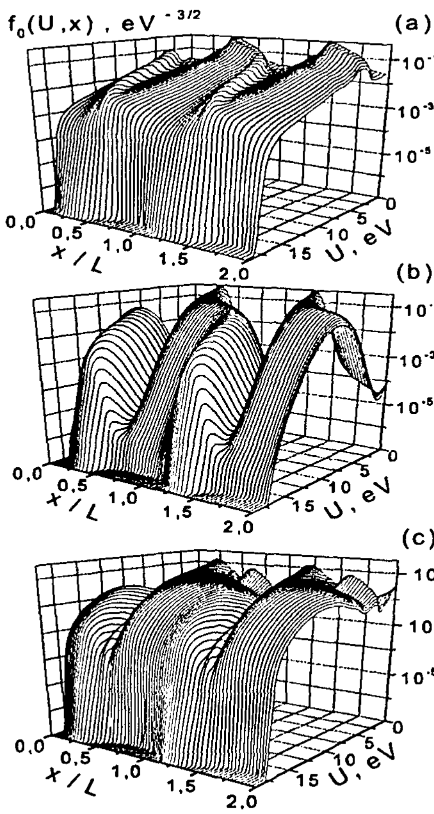

Figure 1: EEDFs calculated in the spatially periodic electric fields with modulation degree $\alpha = 0.9$ for the values of spatial period: (a) $L = 0.9L_{res}$, (b) $L = L_{res}$ and (c) $L = 1.1L_{res}$.

$\delta = 6m^2\nu^2(v_1)U_{ex}/(M(eE_0)^2)$ as follows

$$f_0(\varepsilon, x) = \sum_{i=0} f_0^{(i)}(\varepsilon, x)\delta^i \tag{3}$$

The main term of the expansion (3) can be written as

$$f_0^{(0)} = \Phi(\varepsilon) \int_x^{x_{ex}(\varepsilon)} \frac{dx}{D_\varepsilon} \equiv \Phi(\varepsilon)F(\varepsilon, x) \tag{4}$$

where $\Phi(\varepsilon)$ is the amplitude of the distribution function and $F(\varepsilon, x)$ is the function which is formed in given electric fields when the losses in elastic collisions are neglected.

Accurate numerical solution of equation (1) could be approximated by expression (4). In this case the amplitude $\Phi(\varepsilon)$ can be obtained from the expression

$$\Phi(\varepsilon) = \frac{f_0(\varepsilon, x)}{F(\varepsilon, x)}$$

where $f_0(\varepsilon, x)$ is the strict numerical solution in electric fields with different spatial periods L and $F(\varepsilon, x)$ is given by expression (4).

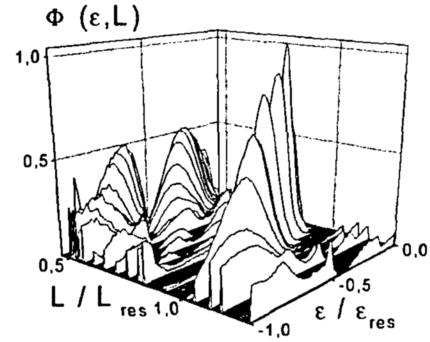

Figure 2: Amplitude of the distribution function $\Phi(\varepsilon)$ calculated for different values of spatial period L.

It is seen from figure 2 that $\Phi(\varepsilon)$ depends resonantly on the value of the spatial period L of electric field.

3. Linear theory of the EEDF formation in weakly modulated periodic electric fields

In the electric fields with small modulation degree an analytical approach to solution of the kinetic equation is possible [1]. It can be shown that the EEDF depends resonantly on the value of the spatial period L. The dependence of the periodic part of the amplitude $\tilde{\Phi}^{(0)}(k)$ on the value of the spatial period L can be written as

$$\tilde{\Phi}^{(0)}(k) = \Phi_{hom}^{(0)} \frac{-ik\beta}{\exp\left(ik(1 + \delta A)\right) - 1 + \delta^2 \mathcal{B} k^2}$$

where $\Phi_{hom}^{(0)}$ is the amplitude of the EEDF in homogeneous field, $k = 2\pi L_{res}/L$ is the dimensionless wavenumber and β, A, $\mathcal{B}$ are the parameters dependent on the modulation degree of the electric field.

4. Acknowledgements

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